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New biostratigraphical constraints for the Norian/Rhaetian boundary: data from Lagonegro Basin, Southern Apennines, Italy

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Four stratigraphic sections belonging to Lagonegro succession (Southern Apennines) at Mt S. Enoc, Pignola-Abriola, Sasso di Castalda and Mt Volturino have been studied in detail under to provide a new micro-palaeontological data set based on conodonts and radiolarians for the characterization of the Norian/Rhaetian interval. The studied sections represent the different settings of the Lagonegro Basin (from proximal to distal facies) and permit a detailed, integrated, biostratigraphy of the Calcari con Selce (cherty limestones) and Scisti Silicei formations (bedded cherts with radiolarians) to be drawn up. The upper portion of the Calcari con Selce Formation, exhibits intermediate characteristics between the Calcari con Selce and Scisti Silicei Formation, in particular the progressive decrease in carbonate content against an increase in shales and cherts. Within the four sections studied, the Norian/Rhaetian interval has been documented both with conodonts and radiolarians. Because of the continuity and the absence of condensed facies, it has been possible to recognize the morphocline between species *Misikella hernsteini* and *Misikella posthernsteini*, here represented by all the transitional forms characterized by common features between the two species, gathered in three evolutionary steps. Moreover, the morphocline between *M. hernsteini* and *M. posthernsteini* has been involved in the definition of the Norian/Rhaetian Boundary, recognizing thus the FAD of *M. posthernsteini*, one of the possible biomarkers proposed for the boundary. The rich, well-preserved, radiolarian associations of Pignola-Abriola, Sasso di Castalda and Mt Volturino permit the correlation of Tethyan and American conodont successions, highlighting the importance of the mostly coincident occurrences of *M. posthernsteini* and *Epigondolella mosheri* morphotype A, which correspond to the base of *Proparvicingula moniliformis* A. Z. and the disappearance of bivalve *Monotis*. These coincident bioevents are used here to define the base of the Rhaetian stage. □ *Biostratigraphy*, *conodonts*, *Lagonegro Basin*, *Late Triassic*, *Norian/Rhaetian boundary*, *radiolarians*.

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The so-called 'Lagonegro sequence' was deposited from Late Palaeozoic to Miocene in the Lagonegro-Molise Basin and is considered part of the Ionian Ocean (Finetti 2005) (the western prolongation of the East Mediterranean ocean in Stampfli & Borel 2002). Its west-dipping subduction below the Calabria–Peloritani arc is still active and was responsible for the Apenninic orogenesis (Finetti 1985, 2005; Ciarapica & Passeri 2002, 2005; Argnani 2005).

The main object of this study was to understand the evolution of this basin and thus to date the beginning of the radiolarian deposition (Scisti Silicei Formation), which characterized the Lagonegro sequence from the Late Triassic to Late Jurassic. This is possible by using detailed biostratigraphy, in this case on the base of conodonts and radiolarians that are abundant and frequent in the Upper Triassic portion of the succession. This study allowed: (1) control the phylogenetic evolution of conodonts in the Norian–Rhaetian time interval; (2) calibration of the biostratigraphic scale based on radiolarians with that based on conodonts; and (3) global correlation of the Lagonegro succession with other palaeogeographic domains.

The Upper Triassic to Upper Jurassic part of the 'Lagonegro sequence' is represented by Calcari con Selce and Scisti Silicei formations. In the upper part of the Calcari con Selce (Transitional Interval of Miconnet 1982; Amodeo 1999) the Norian/Rhaetian Boundary (NRB, hereafter) is well documented and it has been studied in order to provide new data to better define the base of the Rhaetian stage. The Rhaetian represents the last portion of Late Triassic (GTS, Gradstein *et al.* 2004), and was first established by

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Gümbel (1859), based on the occurrence of the bivalve *(Rhaet)Avicula contorta* from Koessen Beds of Austria. The base of the Rhaetian in the Tethyan realm was later defined by Kozur & Mock (1974) with the FAD of the conodont *Misikella posthernsteini*. *Misikella hernsteini*, precursor of *M. posthernsteini* (Mostler *et al.* 1978; Kozur & Mock 1991), was later recognized as a biomarker for the same base (Dagys & Dagys 1994). In North America, the Rhaetian stage has been historically recognized after the extinction of bivalve *Monotis*, occurring in the uppermost portion of radiolarian *Betraccium deweveri* Assemblage Zone (Carter 1993). Thus, Carter (1993) suggested placement of the base of the Rhaetian at the base of the overlying radiolarian *Proparvicingula moniliformis* Assemblage Zone (Carter 1993), which corresponds mostly with the first appearance of *Epigondolella mosheri* morphotype A (e.g. Carter & Orchard 2007). Although ammonoids are the main tool for Middle Triassic and lower Upper Triassic (Julian, lower Carnian) to define Stage boundaries and for detailed biostratigraphy (e.g. Brack *et al.* 2005; Mietto *et al.* 2007), for most of the Upper Triassic (Tuvalian–upper Carnian to Rhaetian) ammonoids are rare, lacking the high degree of correlation potential required for global correlations. Conodonts are instead the main tool in biostratigraphic investigations for Upper Triassic successions (e.g. Rigo *et al.* 2007), and are generally suggested as defining the Carnian/Norian and Norian/Rhaetian boundaries where other physical events are not recognized globally. Furthermore, according to Carter & Orchard (2007) radiolarians are of primary importance for the definition of the NRB due to the apparent provincialism of conodonts and the rarity of ammonoids, permitting also direct correlations between different palaeogeographic domains, such as the Tethyan and North American realms.

Geological setting

The 'Lagonegro sequence' crops out in the Southern Apennines (Fig. 1) and is made up of Permian to Miocene formations, deposited in shallow to deep basinal pelagic environments (Scandone 1967). The lower part of the succession is represented by the 'Lagonegro lower sequence' (e.g. Mostardini & Merlini 1986; Ciarapica *et al.* 1990; Ciarapica & Passeri 2005; Rigo *et al.* 2005), and includes: Monte Facito Formation (Permian to Late Ladinian), Calcari con Selce Formation (Late Ladinian to Rhaetian), Scisti Silicei Formation (Rhaetian to Tithonian) and 'Flysch galestrino' (Tithonian to Early Cretaceous). This lower sequence, always detached from its basement, is now dissected into many tectonic units. These were piled up between the Apenninic and Apulian carbonate platforms (e.g. Mostardini & Merlini 1986) during the Apenninic orogenesis and forming a part of the Southern Apennines chain (Southern Italy).

The Calcari con Selce and Scisti Silicei formations consist of pelagic carbonates, and siliceous deposits (i.e. cherts and radiolarites) bearing conodonts, pelagic bivalves (e.g. genus *Halobia*), radiolarians and rare ammonoids. The Lagonegro successions show different facies associations in the Upper Triassic and Jurassic portions. Based on the amount of resedimented calcarenites and calcirudites shed from adjacent carbonate platforms in both Calcari con Selce and Scisti Silicei formations, Scandone (1967) differentiated the Triassic and Jurassic successions of the Lagonegro

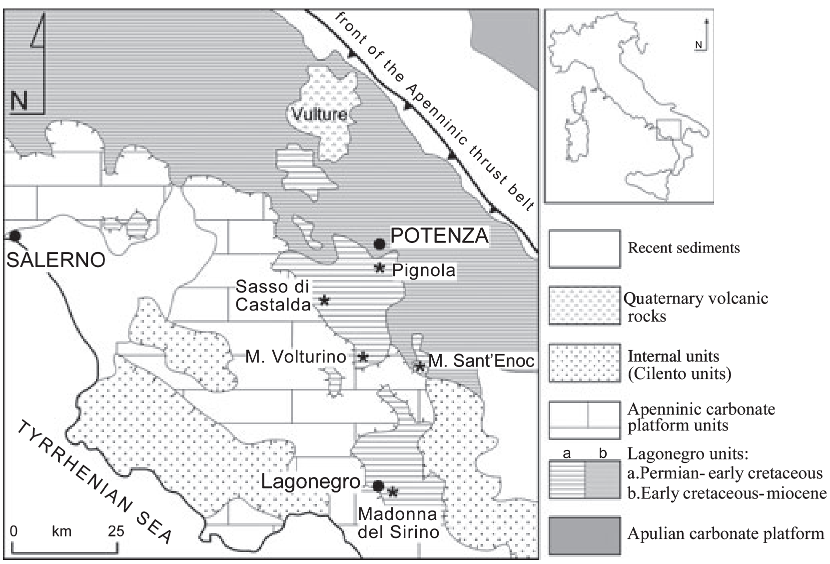

Fig. 1. Schematic geological map of the Southern Apennines with location of the sections studied. Modified from Bertinelli *et al.* (2005a).

Basin in proximal to distal facies. In the proximal facies the Calcari con Selce Formation persisted from Late Triassic to Middle Jurassic times (Selli 1962; Scandone 1967; Bertinelli *et al.* 2005a; Passeri *et al.* 2005). In the distal facies, the transition from the carbonate sedimentation of the Calcari con Selce Formation to the siliceous deposition of Scisti Silicei Formation occurred in different ways between the latest Triassic and the earliest Jurassic. Finding difficulties in placing a boundary between the Calcari con Selce and the overlying Scisti Silicei formations, Miconnet (1982) first introduced the term 'Transitional Interval' for that stratigraphic portion of the Lagonegro succession, where the upper part of the Calcari con Selce Formation contains red radiolaritic intercalations, typical of the overlying Scisti Silicei Formation (for details, see Amodeo 1999; Bertinelli *et al.* 2005a; Passeri *et al.* 2005; Reggiani *et al.* 2005; Giordano *et al.* 2008). In these sections, the base of the Transitional Interval is conventionally marked by a 3-m (from 2.5 to 4 m) thick interval of red shales (Amodeo 1999; Bertinelli *et al.* 2005b; Reggiani *et al.* 2005), a useful lithomarker recognizable throughout the Lagonegro Basin, Sevatian 1 in age (*Mockina bidentata* Zone) (e.g. Rigo *et al.* 2005) (Fig. 2). Afterwards, this interval has been deeply investigated, mostly for biostratigraphic studies (e.g. De Wever & Miconnet 1985; Bertinelli *et al.* 2005a,b; Passeri *et al.* 2005; Reggiani *et al.* 2005; Rigo *et al.* 2005). Furthermore, studying the Scisti Silicei Formation, Amodeo (1999) recognized in the distal facies of this Formation four members that are, in stratigraphic order: the Buccaglione, Nevèra, Serra and Acqua Sulfurea members, considering the Transitional Interval as the upper part of the Calcari con Selce Formation.

Section descriptions

Mt S. Enoc, Pignola-Abriola, Sasso di Castalda and Mt Volturino sections (Fig. 2) are four important sections of the Lagonegro Basin succession where the Norian–Rhaetian interval is well documented and they were investigated for this study. These sections display a good exposure, with an excellent continuity of non-condensed facies of both the Calcari con Selce and Scisti Silicei Formations, allowing detailed sampling for biostratigraphical investigation.

Mt S. Enoc section

The studied Mt S. Enoc section crops out on the right bank of the Alli river, close to Viggiano village (Val d'Agri). The base of the section analysed corresponds to the red shale level, which is 2.5 m in thickness and commonly marks the uppermost portion of the Calcari con Selce Formation. This level (20 m thick) is characterized by an alternation of cherty limestones, thin silicified calcarenites and cherty layers with red and green clayey intercalations (Fig. 2). At 8 m from the base of the section some calciruditic lens-shaped banks occur, containing sub-rounded clasts made of radiolarian-bearing wackestone and packestone reworked as soft pebbles. Afterwards, an alternation of cherty limestones, thin silicified calcarenites, cherty horizons and black cherts and shales follows (30 m thick). Successively, thick layers of cherty limestones (9 m in thickness), mostly silicified, in alternation with clayey shales and thin cherty limestones characterize the final part of the section. In this section, the lowermost member of the Scisti Silicei Formation (Buccaglione member of Amodeo 1999) is not present (N. Giordano, G. Ciarapica, A. Bertinelli & M. Rigo, unpublished data).

Pignola-Abriola section

Pignola-Abriola section was studied along the road connecting Abriola to Potenza on the mountainsides of the Monte Crocetta. It is represented by the upper part of the Calcari con Selce Formation where the Norian–Rhaetian interval is documented (Amodeo *et al.* 1993; Amodeo 1999; Bazzucchi *et al.* 2005; Rigo *et al.* 2005; Tanner *et al.* 2006). The lower part of the section (15 m thick) lacks in the 3-m-thick red shale level that conventionally marks the base of the uppermost portion of the Calcari con Selce Formation and it is characterized by thin-bedded cherty limestones, shales and rare thin layers of calcarenites with fragments of platform-derived benthic organisms (Fig. 2). The carbonate beds, often dolomitized, are mainly mudstones, wackestones and packstones with radiolarians and bivalves (genus *Halobia*). Alternations of dark grey shales, thin beds of limestone and black cherty layers are common in the middle and upper portions of the section (37 m in thickness), representing the upper part of the Calcari con Selce Formation with a progressive decrease in carbonate contents and an increase in shales and black cherts (Bazzucchi *et al.* 2005; Tanner *et al.* 2006). Moreover, in this section the Buccaglione member of the Scisti Silicei Formation is replaced by this upper part of the Calcari con Selce Formation.

Sasso di Castalda section

The Sasso di Castalda succession crops out close to the village of Sasso di Castalda, near Brienza (Potenza), along the south-western slope of Monte Buccaglione (Bertinelli *et al.* 2005a). The attention has

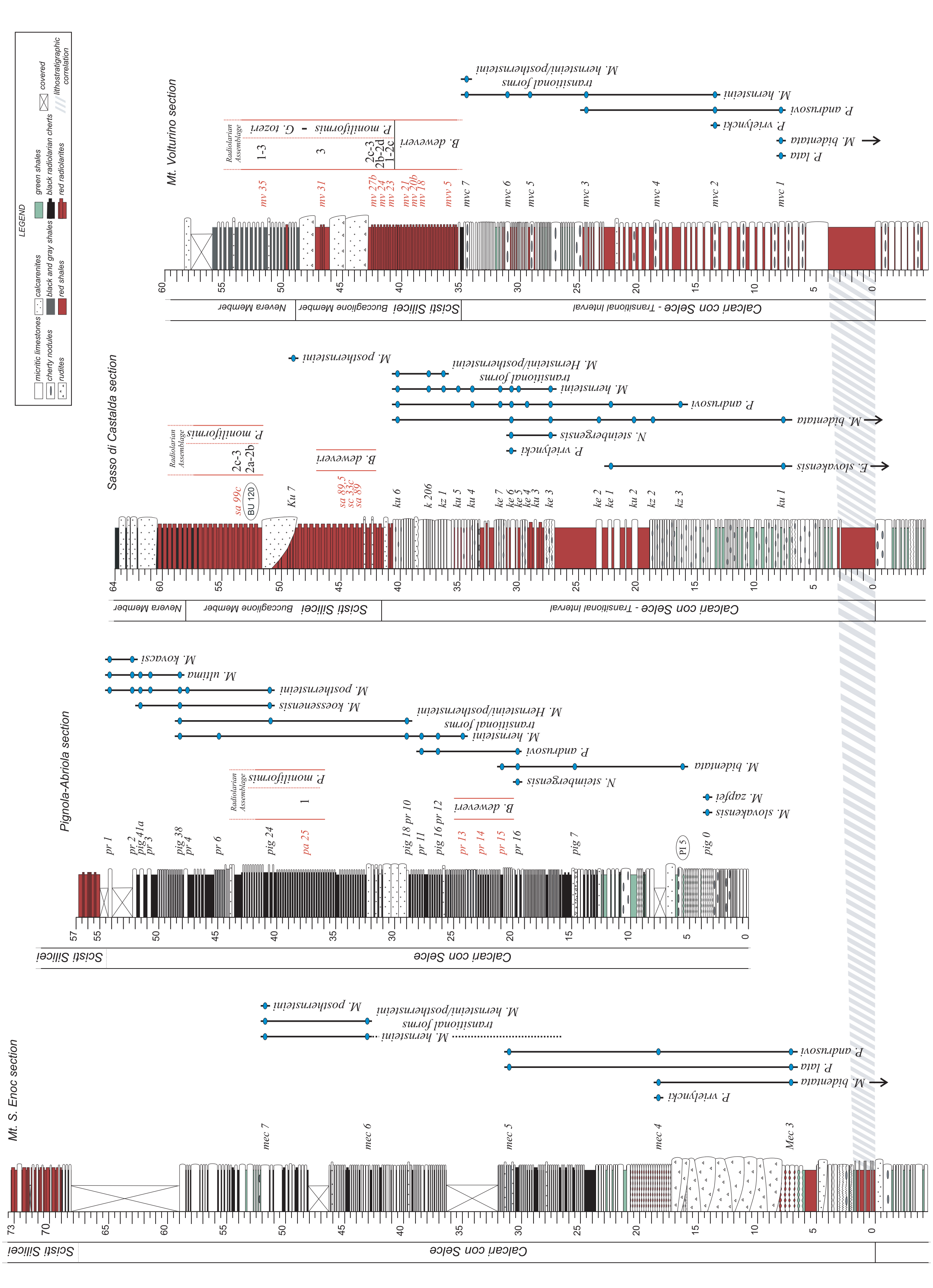

Fig. 2. Stratigraphical sections of the Lagonegro Basin with distribution of the most important conodont and radiolarian biozones. The base of the measured sections is placed with the red shale level of the upper part of Calcari con Selce Formation.

been focused on the Norian–Rhaetian portion of the section, which is represented by Transitional Interval and the first two members of the Scisti Silicei Formation (Buccaglione and Nevèra members). The Transitional Interval is marked by a 3-m-thick red shale level. Above this horizon, thin-bedded cherty limestones are still present, but alternated with red shales and radiolarian-rich levels (radiolarites) for 16 m. Twenty metres above the 3-m-thick red shale level, the calcareous succession is characterized by very thin layers of micritic limestones, partially silicified and thick intercalation of red shales (13 m in thickness) (Fig. 2). Thin-bedded cherty limestones, shales, red cherty layers with radiolarians follow (8 m thick). Towards the top of the section, the sedimentation becomes only siliceous, with siliceous shales, radiolarian cherts and radiolarites of the typical Scisti Silicei Formation and rare calcarenitic bodies (Bertinelli *et al.* 2005a).

Mt Volturino section

The section crops out along the southern slope of the Mt Volturino, characterized by twofolds and highlighted by good exposure of the Calcari con Selce and Scisti Silicei formations. The Mt Volturino section was sampled starting from the 4-m-thick level of red shales that corresponds to the base of the Transitional Interval. Above this horizon, thick-bedded cherty limestones with thin red shale intercalations are followed by thinner cherty limestones intercalated by thick red shales (Fig. 2). Successively, 10 m of thin cherty limestones and red shales alternate with red cherts, and radiolarites occur. Where thin shales, cherty layers and radiolarites become common, the Buccaglione Member (Scisti Silicei Formation) conventionally begins. Above, the transition to Nevèra member is characterized by 1 m of thin calcarenites alternate with green shales passing to an alternation of black siliceous shales and silicified calcarenites rich in organic matter, peculiar of the Nevèra member (Fig. 2) (N. Giordano, G. Ciarapica, A. Bertinelli & M. Rigo, unpublished data).

Biostratigraphy

The distribution of the most biostratigraphically significant conodonts is shown in Fig. 2, where the assemblages of the conodonts and radiolarians found in Mt S. Enoc, Pignola-Abriola, Sasso di Castalda and Mt Volturino sections are described. An occurrence chart for the radiolarians in Pignola-Abriola, Sasso di Castalda and Mt Volturino sections is given in Table 1. The biozonations proposed by Kozur & Mock (1991) and Carter (1993) for conodonts and radiolarians have been adopted for this paper.

Mt S. Enoc section

The upper part of Calcari con Selce Formation has been sampled for conodont investigation. The assemblage recorded in sample mec3, located 5 m above the red shale level (Fig. 2), consists of *M. bidentata*, *Parvigondolella andrusovi*, *Parvigondolella lata* and transitional forms between *M. bidentata* to *P. andrusovi*. The same assemblage without *P. lata* but with *Parvigondolella vrielyncki* (Fig. 3) has been found in sample mec4. *Parvigondolella lata* and *P. andrusovi* characterize the poor assemblage of the sample mec5. In the upper part of the section (sample mec6; Fig. 2), ca. 12 m above sample mec5, *M. hernsteini* first occurs (FO) together with transitional forms between *M. hernsteini* to *M. posthernsteini*. The last sample for conodont investigations (mec7) provides the first specimen of *M. posthernsteini*. At the Mt S. Enoc section the *M. hernsteini–P. andrusovi* Zone characterizes the middle part of the studied section and the appearance of *M. posthernsteini* marks the base of the *M. posthernsteini* Zone in the upper part. Conodont CAI corresponds to 3 (Epstein *et al.* 1977).

Pyritized radiolarians are present in samples mec4 and mec6, but the preservation is very poor preventing specific determination. Unfortunately, the base of the Scisti Silicei Formation does not provide radiolarians.

Pignola-Abriola section

Rich assemblages of conodonts and pyritized radiolarians occurred throughout the section (Bazzucchi *et al.* 2005; Rigo *et al.* 2005). Here, we describe the integration of new data (Fig. 3) with those previously illustrated by different authors (e.g. Amodeo 1999; Bazzucchi *et al.* 2005) but re-interpreted after new conodont palaeontological/biostratigraphical studies (e.g. Kozur 2003; Moix *et al.* 2007).

At the base of the studied section, sample pig0 is characterized by the presence of *Mockina zapfei* (=*Epigondolella postera* in Bazzucchi *et al.* 2005) and *Mockina slovakensis* (Fig. 2). *Mockina bidentata* occurs 2.5 m above the first sample (PI5 from Mastandrea *et al.* 2003). *Mockina bidentata*, *Norigondolella steinbergensis* and *P. andrusovi* are present in sample pr16. *Misikella hernsteini* first occurs in sample pr13 and pig16-pr12-pr11 are characterized by *P. andrusovi*. At pig16, a specimen of *M. posthernsteini* has been collected (Kozur, personal communication *in* Tanner *et al.* 2006), but this specimen has never been illustrated and its occurrence is inconsistent with the

Table 1. Occurrence chart for radiolarians in Pignola-Abriola, Sasso di Castalda and Mt Volturino sections.

Samples	Pignola-Abriola section				Sasso di Castalda section					Mt Volturino section										
Taxa	pr15	pr14	pr13	pa25	sa89	sc33c	sa89	BU120	sa99c	mvc4	mvv5	mv19	mv20b	mv21	mv23	mv24	mv25	mv27b	mv31	mv35
Betraccium deweveri		●									●	●		●						
Betraccium sp. aff. *B. deweveri*					●	●	●							●						
Citriduma sp. A, *sensu* Carter (1993)			●								●									
Citriduma sp. cf. C. sp. A, *sensu* Carter (1993)		●																		
Betraccium maclearni													●							
Ayrtonius elizabethae	●	●	●							●										
Lysemelas sp. cf. *L. olbia*	●	●																		
Praemesotaturnalis gracilis		●																		
Livarella sp. 11, *sensu* Carter (1993)		●																		
Tetraporobrachia sp. aff. *T. composita*		●																		
Globolaxtorum sp. cf. *G. hullae*		●																		
Livarella valida	●	●							●										●	
Fontinella primitiva				●																
Praemesosaturnalis sp. cf. *P. sandspitensis*				●					●											
Betraccium inornatum																●				
Betraccium sp. aff. *B. inornatum*								●					●							
Paraonella pacofiensis								●	●						●					
Pseudohagiastrum sp. A, *sensu* Carter (1993)															●					
Tetraporobrachia sp. C, *sensu* Carter (1993)								●												
Praecitriduma sp. cf. *P. apexensis*									●											
Pantanellium newkluense								●												
Fontinella clara								●	●											
Proparvicingula sp. cf. *P. moniliformis*								●												
Livarella sp. cf. *L. densiporata*								●												
Sirella sp. cf. *S. tledoensis*									●										●	
Haeckelicyrtium sp. cf. *H. karcharos*																●				
Eptingium sp. cf. *E. amoenum*																●				
Ferresium triquetrum									●								●			
Bipedis triassicus																				
Sirella sp. aff. *S. tledoensis*																		●		
Octostella dihexacanthus																			●	
Praemesosaturnalis sp. aff. *P. sandspitensis*																			●	
Pseudohagiastrum giganteum																			●	
Livarella magna																				●

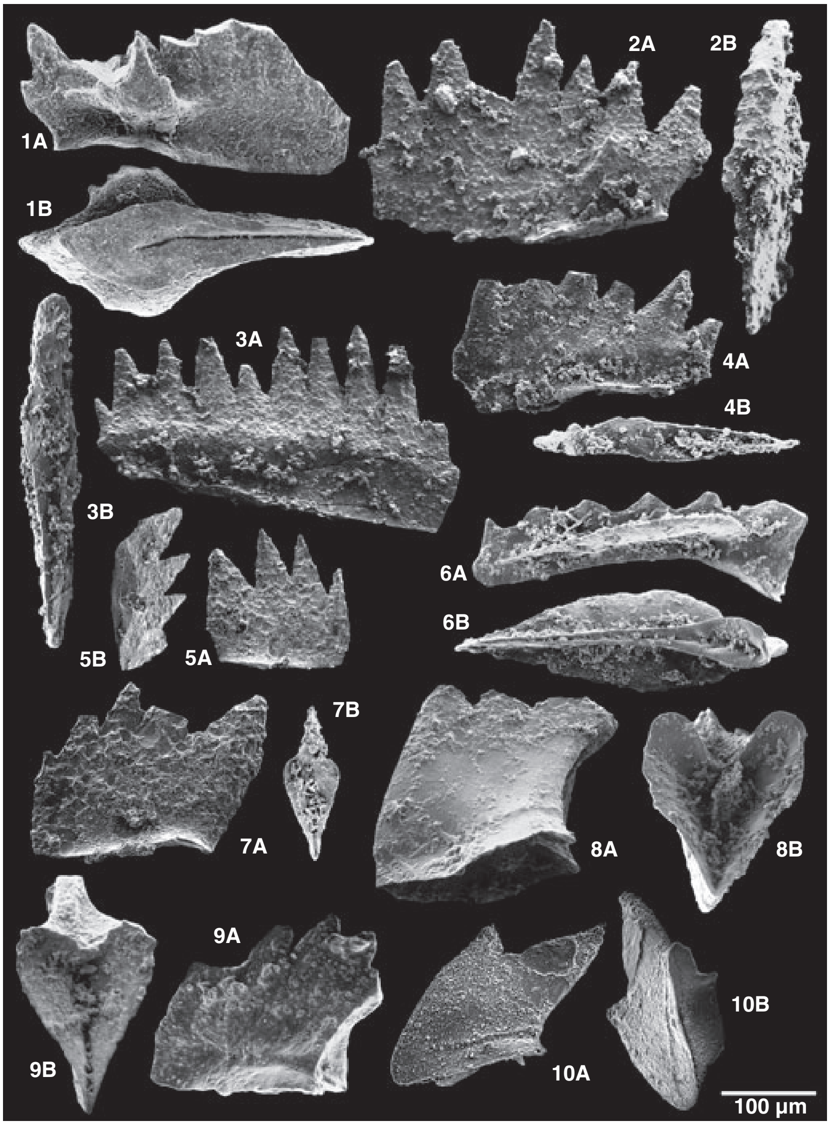

Fig. 3. Upper Norian and Rhaetian conodonts from Lagonegro. Scale bar = 100 μm. 1A, B, *Mockina bidentata* (Mosher), Calcari con Selce Formation, Pignola-Abriola section sample pr15. 2A, B, *M. bidentata* (Mosher); Calcari con Selce Formation, Mt S. Enoc section sample mec3. 3A, B, *Parvigondolella vrielyncki* Kozur & Mock 1972; Calcari con Selce Formation, Mt S. Enoc section sample mec4. 4A, B, *P. andrusovi* Kozur & Mock; Calcari con Selce Formation, Mt S. Enoc section sample mec5. 5A, B, *Parvigondolella lata* Kozur & Mock 1974; Calcari con Selce Formation (Transitional Interval), Mt Volturino section sample mvc1. 6A, B, *Norigondolella steinbergensis* (Mosher), Calcari con Selce Formation, Pignola-Abriola section sample pr16. 7A, B, *Misikella hernsteini* (Mostler); Calcari con Selce Formation (Transitional Interval), Sasso di Castalda section sample kz1. 8A, B, *M. posthernsteini* Kozur & Mock 1974; Calcari con Selce Formation, Pignola-Abriola section sample pr3. 9A, B, *Misikella ultima* Kozur & Mock, Calcari con Selce Formation, Pignola-Abriola section sample pig40. 10A, B, *Misikella kovacsi* Orchard, Calcari con Selce Formation, Pignola-Abriola section sample pig40.

conodont distribution of this study, considering also the beginning of the *M. hernsteini/posthernsteini* morphocline (pig18), ca. 3 m above pig16. At 40 m from the base, in the sample pig24, *M. posthernsteini* occurs with *Misikella koessenensis*. The sample pig38 provides a rich assemblage of conodonts, including *M. koessenensis*, *M. posthernsteini* and the first occurrence of *Misikella ultima* (Bazzucchi *et al.* 2005; Rigo *et al.* 2005). Moreover, a single element of *M. hernsteini* with transitional forms between *M. hernsteini/posthernsteini* has been collected from sample pig38. The samples pr3 and pig41a are characterized by the presence of *M. posthernsteini* and *M. ultima*, along with *M. koessenensis* in sample pig41a only. The last two samples (pr2 and pr1) provide *M. posthernsteini*, *M. ultima* and *Misikella kovacsi*. Conodont CAI is 1.5 (Epstein *et al.* 1977; Di Leo *et al.* 2003).

New data on radiolarian biostatigraphy have been obtained from sample pr14, and partially from samples pr15 and pr13 (Fig. 4). The collected radiolarians were pyritized and well preserved. Sample pr14 is characterized by a rich radiolarian association

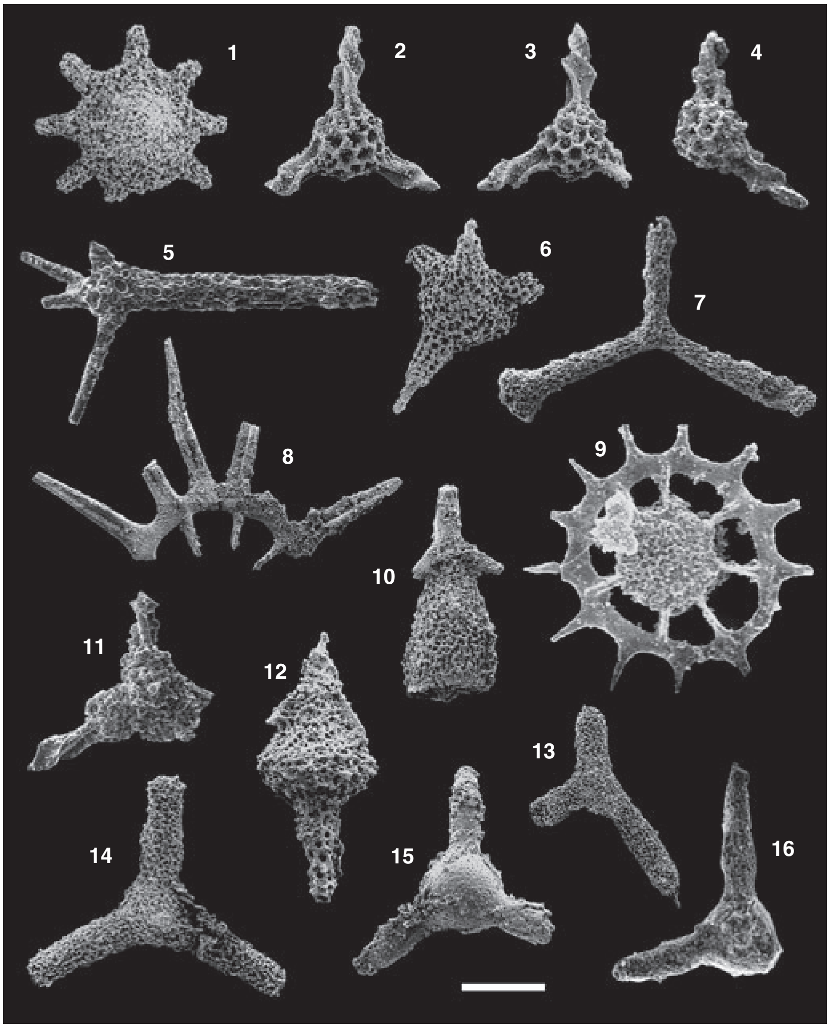

Fig. 4. Upper Norian and Rhaetian radiolarians from Lagonegro. Scale bar = 100 μm for 2–5, 9, 11, 12, 15, 16; 150 μm for 8, 10; and 200 μm for 1, 6, 7, 13, 14. 1, *Citriduma* sp. A, *sensu* Carter (1993), Calcari con Selce Formation, Pignola-Abriola section sample pr13. 2, 3, *B. deweveri* Pessagno & Blome, Calcari con Selce Formation, Pignola-Abriola section sample pr14. 4, *Betraccium* sp. aff. *B. deweveri* Pessagno & Blome, Scisti Silicei Formation (Buccaglione member), Sasso di Castalda section sample sc33. 5, *Pseudohagiastrum giganteum* Carter & Hori, Scisti Silicei Formation (Buccaglione member), Mt Volturino section sample mv31. 6, *Tetraporobrachia* sp. aff. *T. composita* Carter, Calcari con Selce Formation, Pignola-Abriola section sample pr14. 7, *P. pacofiensis* Carter, Scisti Silicei Formation (Buccaglione member), Mt Volturino section sample mv23. 8, *Praemesotaturnalis gracilis* (Kozur & Mostler), Calcari con Selce Formation, Pignola-Abriola section sample pr14. 9, *Praemesosaturnalis* sp. aff. *P. sandspitense* (Blome), Scisti Silicei Formation (Buccaglione member), Mt Volturino section sample mv31. 10, *Lysemela* sp. cf *L. olbia* Sugiyama, Calcari con Selce Formation, Pignola-Abriola section sample pr15. 11, *Sirella* sp. aff. *S. tledoensis* (Carter), Scisti Silicei Formation (Buccaglione member), Mt Volturino section sample mv31. 12, *Globolaxtorum* sp. cf. *G. hullae* (Yeh & Cheng), Calcari con Selce Formation, Pignola-Abriola section sample pr14. 13, *Ayrtonius elizabethae* Sugiyama, Calcari con Selce Formation, Pignola-Abriola section sample pr15. 14, *Livarella* sp. 11, *sensu* Carter (1993), Calcari con Selce Formation, Pignola-Abriola section sample pr14. 15, *Livarella valida* Yoshida, Calcari con Selce Formation, Pignola-Abriola section sample pr15. 16, *Livarella magna* Tekin, Scisti Silicei Formation (Buccaglione member), Mt Volturino section sample mv31.

consisting in *Citriduma* sp. cf. *C.* sp A, *sensu* Carter (1993), *B. deweveri*, *Ayrtonius elizabethae, Lysemela* sp. cf. *L. olbia, Praemesotaturnalis gracilis, Livarella valida, Livarella* sp. 11, *sensu* Carter (1993), *Globolaxtorum* sp. cf. *G. hullae* and *Tetraporobrachia* sp. aff. *T. composita* providing a Late Norian age (*B. deweveri* Assemblage Zone). Instead, from sample pr15 only *A. elizabethae, Lysemela* sp. cf. *L. olbia* and *L. valida* have been found, as in sample pr13 only *Citriduma* sp. aff. *C.* sp. A, *sensu* Carter (1993) and *A. elizabethae* have been determined. At 38 m from the base of the section (sample pa25), Bazzucchi *et al.* (2005) described a lower Rhaetian radiolarian assemblage including *Fontinella primitiva*, *Globolaxtorum* sp. cf. *G. hullae* and *Praemesosaturnalis* sp. cf. *P. sandspitensis* (*P. moniliformis* Zone, assemblage 1).

Sasso di Castalda section

Here, we present a summary of all biostratigraphical data from Sasso di Castalda section including also the new data (samples kz and ke) obtained after

Bertinelli *et al.* (2005a). *Mockina bidentata* and *M. slovakensis* are present in the first sample (ku1) above the red shales level (Fig. 2). The sample kz3 contain only *P. andrusovi*. *Mockina bidentata*, *Epingondolella slovakensis* and *P. andrusovi* characterizing the lower part of the Transitional Interval (kz2, ku2, ke1 and ke2). In the upper part of the section *M. hernsteini* occurs (Fig. 3), along with *P. andrusovi*, *M. bidentata* and *N. steinbergensis* (sample ke3). A rich assemblage was found in sample ke6, with *M. hernsteini*, *P. andrusovi*, *M. bidentata*, *N. steinbergensis* and *P. vrielyncki*. *Misikella hernsteini* and *P. andrusovi* characterize the rest of the Transitional Interval up to the beginning of the Scisti Silicei Formation. Eight metres above the base of Buccaglione member, *M. posthernsteini* occurs, at the base of a 2- to 3-m-thick calcarenite unit. *Misikella posthernsteini* occurred after the morphocline of *M. hernsteini/posthernsteini* and it has been thus interpreted as an FAD (Remane 2003), even if it was collected at the base of the 2- to 3-m-thick calcarenite. Conodont CAI corresponds to 2.5 (Epstein *et al.* 1977; Di Leo *et al.* 2003; Bertinelli *et al.* 2005a).

Above the calcarenite bed, a Rhaetian radiolarian association (sample sa99c) was illustrated by Bertinelli *et al.* (2005a), consisting of: *Ferresium triquetrum*, *L. valida, Praemesosaturnalis* sp. cf. *P. sandspitensis, Paraonella pacofiensis, Praecitriduma* sp. cf. *P. apexensis, Fontinella clara, Sirella* sp. cf. *S. tledoensis* (*P. moniliformis–Globolaxtorum tozeri* Zone, assemblage 2c-3). Furthermore, Amodeo (1999) assigned the sample BU120 (ca. 1 m above the 2- to 3-m-thick calcarenite in which *M. posthernsteini* occurred) to the *P. moniliformis* Zone (assemblage 2a–2b).

The new radiolarian assemblages found in the lower part of Buccaglione member comes from samples sa89, sc33c and sa89.5, 5 m below the calcarenites. Although radiolarians are poorly preserved some specimens of species *B. deweveri* have been determined (Fig. 4).

Mt Volturino section

The Transitional Interval yielded a rich assemblage of conodonts (Fig. 3) and several pyritized radiolarians, while the Buccaglione member and part of the Nevèra member of the overlying Scisti Silicei Formation provided assorted assemblages of well-preserved radiolarians (Fig. 4) but lacking conodonts.

The first sample (mvc1) of the Transitional Interval (Fig. 2), 4 m above the red shale level, is characterized by the presence of *M. bidentata, P. andrusovi*, *P. lata* and transitional forms between *M. bidentata* to *P. andrusovi*. In sample mvc2, at 14 m from the base of the section, *M. hernsteini* occurs, along with *P. andrusovi*, *P. vrielyncki* but without *M. bidentata.* This conodont association represents the *M. hernsteini–P. andrusovi* Zone, *sensu* Kozur & Mock (1991) and characterizes the rest of the Transitional Interval up to the beginning of the Scisti Silicei Formation. The genus *Parvigondolella* dominates in the lower part of this conodont zone, while genus *Misikella* becomes dominant in the upper part, where transitional forms between *M. hernsteini* and *M. posthernsteini* have been documented. Conodont CAI is 3 (Epstein *et al.* 1977).

Some radiolarians are present at the sample mvc4, while pyritized radiolarians in association with a rich assemblage of conodonts occur at 34 m at sample mvc7. Unfortunately, radiolarians from the Transitional Interval are very poorly preserved and only one specimen in sample mvc4 of species *A. elizabethae* has been determined.

From metre 35, at the base of the Scisti Silicei Formation, up to metre 40, a rich radiolarians assemblage consisting of *Citriduma* sp. A, *sensu* Carter (1993), *B. deweveri*, *Betraccium* sp. aff. *B. deweveri, Betraccium maclearni*, *Betraccium* sp. aff. *Betraccium inornatum* (samples mvv5, mv18, mv20b and mv21) has been collected, providing the Norian age of the lower part of Buccaglione member (*B. deweveri* Assemblage Zone).

The remaining part of Buccaglione member, from 40 to 48 m (samples mv23, mv24, mv25, mv27, mv27b and mv31), according to Carter (1993), is characterized by a well-preserved Rhaetian radiolarian association (*P. moniliformis–G. tozeri* Zone, assemblage 1–3), composed of *P. pacofiensis*, *Pseudohagiastrum* sp. A, *sensu* Carter (1993), *B. inornatum, Orbiculiforma* sp., *F. triquetrum*, *Canoptum* sp., *Sirella* sp. aff. *S. tledoensis*, *Pseudohagiastrum giganteum*, *Haeckelicyrtium* sp. cf. *H. karcharos*, *Eptingium* sp. cf. *E. amoenum*, *B. triassicus*, *Praemesosaturnalis* sp. aff. *P. sandspitensis*, *L. valida*, *O. dihexacanthus*.

At metre 48, the onset of Nevèra member (Scisti Silicei Formation) is recorded but the poorly preserved radiolarian species *Livarella magna* and *Sirella* sp. from sample mv35, permitted the first part of this member to be referred to the Rhaetian.

Discussion

Morphocline of Misikella hernsteini/posthernsteini

The excellent continuity and the absence of condensed facies of the Calcari con Selce and Scisti Silicei Formations of the Mt S. Enoc, Pignola-Abriola, Sasso di Castalda and Mt Volturino sections permitted the

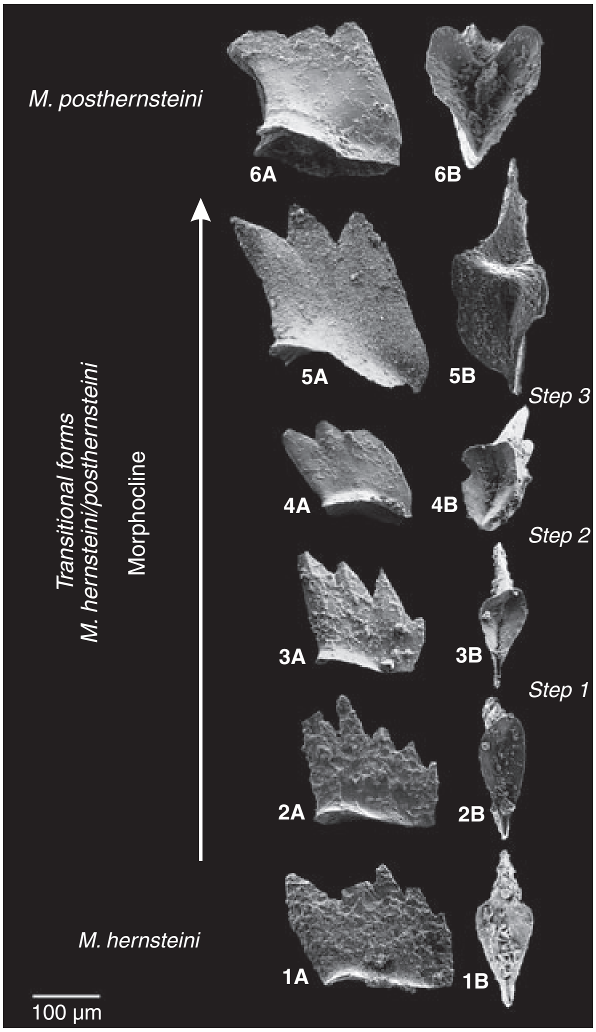

Fig. 5. Evolutionary trend between *Misikella hernsteini* and *Misikella posthernsteini* with the three evolutionary steps of the morphocline. Scale bar = 100 μm. 1A, B, *M. hernsteini* (Mostler); Calcari con Selce Formation (Transitional Interval), Sasso di Castalda section sample kz1. 2A, B, *M. hernsteini* (Mostler); Calcari con Selce Formation (Transitional Interval), Sasso di Castalda section sample kz1. 3A, B, transitional form between *M. hernsteini* to *M. posthernsteini*, Calcari con Selce Formation, Mt S. Enoc section sample mec6. 4A, B, transitional form between *M. hernsteini* to *M. posthernsteini*, Calcari con Selce Formation, Mt S. Enoc section sample mec7. 5A, B, *M. posthernsteini* Kozur & Mock 1974; Calcari con Selce Formation, Pignola-Abriola section sample pr2. 6A, B, *M. posthernsteini* Kozur & Mock 1974; Calcari con Selce Formation, Pignola-Abriola section sample pr3.

collection of a well-preserved assemblage of conodonts, from which transitional forms between *M. bidentata* to *P. andrusovi* and *M. hernsteini* to *M. posthernsteini* have been identified (Fig. 5). Similar transitional forms, such as *M. bidentata* to *M. hernsteini* and *M. bidentata* to *P. andrusovi* have been already described by different authors from Lagonegro successions (Bazzucchi *et al.* 2005; Bertinelli *et al.* 2005a; Rigo *et al.* 2005; Giordano *et al.* 2008). In this paper, we describe the morphocline between *M. hernsteini* and *M. posthernsteini*, consisting of transitional forms arranged in three evolutionary steps. *Misikella hernsteini* and *M. posthernsteini* belong to the same genus and are thus characterized by the same conodont apparatus (e.g. Fåhræus & Ryley 1989; Pálfy *et al.* 2007). According to Remane (2003) morphoclines are basic for the identification of the First Appearance Datum (FAD), in this case the FAD of *M. posthernsteini*, largely used for the definition of the NRB (Kozur & Mock 1974, 1991; Moix *et al.* 2007; Krystyn *et al.* 2007a,b). A similar approach has been already applied for the candidature of Pizzo Mondello section (Sicily, Italy) to define the base of the Norian Stage (e.g. Mazza & Rigo 2008; Mazza *et al.* 2009).

According to Mostler *et al.* (1978) and Kozur & Mock (1991), *M. posthernsteini* directly descends from *M. hernsteini* by a reduction in the blade denticle number and development of a heart-shaped basal cavity. Because of the finding of these transitional forms in the studied sections, it has been possible to highlight the main features involved in *M. hernsteini*–*M. posthernsteini* evolution, in stratigraphical order. *Misikella hernsteini* is usually characterized by a long and narrow drop-shaped basal cavity, and a laterally pressed blade composed of five to six denticles; instead, *M. posthernsteini* bears 3 (rarely 4) thick denticles on the blade, a wide heart-shaped basal cavity and a deep incision on the cusp backside. Both these two species have the cusp as the last posterior blade denticle, according to Moix *et al.* (2007). In the first step of evolution from *M. hernsteini* to *M. posthernsteini*, the shape of the basal cavity starts to enlarge in the posterior part and contemporaneously the number of blade denticles decreases, creating transitional forms with four-denticle blade and a large drop-shaped basal cavity (triangle in shape), without any inflexion peculiar of the heart (Fig. 5). Second step, the first denticle of the blade, opposite to the cusp, becomes increasingly smaller until it combines with the second one and a little inflexion occurs on the posterior basal cavity margin. No incision, or a very superficial one, on the cusp backside is present (Fig. 5). At the third step, only three denticles form the blade, even if a vestigial one could be present on the anterior side of the first denticle, the basal cavity obtains the typical heart shape of the *M. posthernsteini* and a deep incision furrows the backside of the cusp. This incision probably develops owing to the inflexion of the heart-shaped basal cavity (Fig. 5).

After a careful investigation of the transitional forms belonging to the *M. hernsteini/posthernsteini* morphocline, we consider the shape of the basal cavity as the main feature identifying species *M. posthernsteini* and we thus suggest to consider only those specimens with a strong inflexion on the posterior margin of the basal cavity (heart shape) and with an evident furrow on the cusp backside, as real *M. posthernsteini*.

Chronostratigraphic implications for the Norian/Rhaetian boundary

Conodont assemblages of this study are comparable with those found in other sections of the Lagonegro Basin (Bazzucchi *et al.* 2005; Bertinelli *et al.* 2005a; Rigo *et al.* 2005), where the base of the Rhaetian has been identified with the first occurrence of *M. hernsteini*, as suggested by the International Commission on Stratigraphy (Dagys & Dagys 1994). Thus, the NRB was first placed in the Transitional Interval between Calcari con Selce and Scisti Silicei formations in both distal and proximal facies successions (Bazzucchi *et al.* 2005; Bertinelli *et al.* 2005a; Rigo *et al.* 2005). Kozur & Mock (1991) suggested instead placement of the base of the Rhaetian with the FAD of *M. posthernsteini* because of its easy recognition and wide distribution (Kozur 2003). Basing on this occurrence, in the Mt S. Enoc and at Pignola-Abriola sections it is possible to place the NRB in the upper part of the Calcari con Selce Formation. Instead, *M. posthernsteini* occurred in the Buccaglione member of Scisti Silicei Formation in the Sasso di Castalda section and it should also be present in the same member of Mt Volturino section, but the cherty and highly silicified lithologies peculiar to the Scisti Silicei Formation prevents collection of conodonts with standard techniques.

Radiolarians collected in the first part of Buccaglione member (lowermost member of Scisti Silicei Formation) of Mt Volturino section, however, are late Norian in age (*B. deweveri* A. Z) due to the presence of *B. deweveri* and *Citriduma* sp. A, according to the radiolarian biozonation proposed by Carter (1993). The remaining part of Buccaglione member is characterized by a Rhaetian radiolarian association (*P. moniliformis–G. tozeri* A. Z.) due to the presence of *P. pacofiensis*, *Pseudohagiastrum* sp. A, *sensu* Carter (1993), *F. triquetrum*, *B. triassicus*, *P. giganteum*, *O. dihexacanthus* and *Sirella* sp. aff. *S. tledoensis*. Based on these new biostratigraphic occurrences, within the Mt Volturino section the NRB has been placed within the Buccaglione member, referring the base of the Scisti Silicei Formation to upper Norian. Similar radiolarian associations have been also collected in the Buccaglione member of Sasso di Castalda section where the *P. moniliformis* A. Z. (Amodeo 1999), commonly considered to be Rhaetian in age (Carter 1993), occurred above the occurrence of *M. posthernsteini* (Bertinelli *et al.* 2005a). Below this occurrence the Norian *B. deweveri* A. Z., *sensu* Carter (1993) has been documented, according also to data from Amodeo (1999).

In all the sections investigated for this study, transitional forms characterizing the *M. hernsteini/posthernsteini* morphocline have been collected, permitting thus to recognize the FAD of *M. posthernsteini* at Mt S. Enoc, Pignola-Abriola and Sasso di Castalda sections, as shown in Fig. 2. In particular, at Sasso di Castalda and Mt Volturino sections this morphocline have been collected in the uppermost portion of the *B. deweveri* A. Z., *sensu* Carter (1993). Considering the transitional forms of *M. hernsteini/posthernsteini* morphocline we interpreted the occurrence of *M. posthernsteini* of Mt S. Enoc, Pignola-Abriola and Sasso di Castalda sections as real FAD, according to Remane (2003).

Because of the joint occurrence (at least at Sasso di Castalda and Mt Volturino sections) of radiolarians associations and *M. hernsteini/posthernsteini* morphocline, it is thus possible to appraise the chronostratigraphic implications of the *M. hernsteini/posthernsteini* morphocline and the relative FAD of *M. posthernsteini* to the NRB.

Recently, Krystyn *et al.* (2007a) proposed new magneto- and biostratigraphical constraints for the NRB studying the Steinbergkogel section (Austria) and they suggested this section as a candidate for the base of the Rhaetian stage (GSSP). Two conodont biomarkers have been proposed for the base of the Rhaetian at the Steinbergkogel section: Option 1 with the FO of *M. hernsteini* (ICS, Dagys & Dagys 1994); and Option 2 with the FAD of *M. posthernsteini* (e.g. Kozur & Mock 1991; Muttoni *et al.* 2009; Rigo *et al.* 2009). Alternatively, in North America it is largely accepted that the occurrence of conodont *E. mosheri* morphotype A is a biomarker for the base of the Rhaetian stage, the occurrence of which is well calibrated with the beginning of the radiolarian *Propavicingula moliniformis* A. Z. (e.g. Carter & Orchard 2007).

New data from Austria (Krystyn *et al.* 2007b) documented the Tethyan occurrences of *Epigondolella englandi* and *E. mosheri* morphotype A and morphotype B (*sensu* Orchard *et al.* 2007) compared with the occurrences of the two Tethyan conodont species *M. hernsteini* and *M. posthernsteini*, proposed as characterizing the base of the Rhaetian stage (respectively, Option 1 and Option 2 by Krystyn *et al.* 2007a,b). In Austria, *E. mosheri* morphotype A and B occurred together at the level of *M. hernsteini* and they are characterized by a short range within the lower portion of *M. hernsteini* stratigraphical distribution (Option 1). In North America, the *E. mosheri* morphotype B first occurs below *E. mosheri* morphotype A, within the radiolarian *B. deweveri* A. Z. (Carter & Orchard 2007). It is thus possible to state that the occurrence of *E. mosheri* morphotype B at Steinbergkogel section is a local appearance. As in the Austrian section the occurrences of *E. mosheri* morphotype A (and B) are coincident with the occurrences of *M. hernsteini* (Krystyn *et al.* 2007b), the base of the North American radiolarian *P. moniliformis* A. Z. would thus calibrate with the occurrence of *M. hernsteini* (*sensu* Krystyn *et al.* 2007a,b), highlighting the importance of Option 1 (*M. hernsteini*) for the base of the Rhaetian.

Data from the Lagonegro Basin prove that the appearance of *M. hernsteini* clearly first occurs within the *B. deweveri* radiolarian Zone (Fig. 2), far below the *P. moniliformis* A. Z. (more than 25 m in Sasso di Castalda and Mt Volturino sections and ca. 13 m in Pignola-Abriola). Thus, the occurrence of *M. hernsteini* in Steinbergkogel section does not represent the first appearance. In North America, the first occurrence of conodont *E. mosheri* morphotype A mostly coincides with the base of radiolarian *P. moniliformis* A. Z. (Carter & Orchard 2007).

Likewise, in the Lagonegro Basin, the appearance of *M. posthernsteini* occurs in the lowermost portion of *P. moniliformis* A. Z., in particular in the Assemblage 1 according to Carter (1993), as highlighted by conodont and radiolarian distributions of Pignola-Abriola section and in agreement with that of Sasso di Castalda. It is thus possible to state that the first occurrence of conodont *E. mosheri* morphotype A is equivalent to *M. posthernsteini* in age, and that are mostly coincident with the base of *P. moniliformis* A. Z. We thus suggest the use one of these three bioevents to identify the NRB worldwide.

This new calibration is also confirmed by the macrofossil association collected in Steinbergkogel section, in particular by the disappearance of large *Monotis* bivalves, historically considered for the identification of the NRB, that occurs in the uppermost *B. deweveri* A. Z. in North America strata, a little below the beginning of radiolarian *P. moniliformis* A. Z. (e.g. Carter & Orchard 2007), which is mostly coeval to *M. posthernsteini*.

In the Steinbergkogel section (Austria) the large bivalve *Monotis* disappears a little below the occurrence of *E. mosheri* morphotype A (Krystyn *et al.* 2007a,b) as in North America, but it disappears just below *M. hernsteini* and not below the *M. posthernsteini* occurrence as expected, after calibrations with the conodont and radiolarian distributions recorded in the Lagonegro Basin. Thus, the appearance of *M. posthernsteini* of Steibergkogel section (Krystyn *et al.* 2007a,b) has to be considered as a local occurrence (FO), as it occurs above the occurrence of *E. mosheri* morphotype A and no transitional forms of *M. hernsteini/posthersteini* have been documented. Instead it would be expected that *M. posthernsteini* should first appear at the same level of *E. mosheri* morphotype A and that *M. hernsteini* and *E. mosheri* morphotype B should occur somewhere below the older layer in which *E. mosheri* morphotype A has been collected. After these new data from the Lagonegro Basin, all the other biostratigraphical events suggested as proxies for Options 1 and 2 at Steinbergkogel section (Krystyn *et al.* 2007a,b) should thus be reconsidered.

Conclusions

Throughout the Lagonegro Basin the Norian–Rhaetian interval is well documented and new biostratigraphical data, the result of conodont and radiolarian investigations, allowed us to improve biostratigraphical resolution to better define the NRB. In particular, three evolutionary steps have been identified in the morphocline between the conodont species *M. hernsteini* and *M. posthernsteini*, the latter is one of the possible biomarker proposed for the NRB. In stratigraphic order, these three steps are: (1) enlargement of the basal cavity in its posterior portion (triangle in shape) and decrease in number of blade denticles; (2) inflexion on the posterior margin of the basal cavity, and presence of the first denticle, almost shortened, stuck on the second one; and (3) heart-shaped basal cavity that produced a deep furrow on the cusp backside and three (four) sharp denticles forming the blade.

Only by refining the phylogenetic relationships between two species it is possible to recognize the real FAD of the descendant, and in this case, the recognition of conodont transitional forms belonging to the *M. hernsteini/posthernsteini* morphocline contributes to delineate the base of the Rhaetian stage (FAD of *M. posthernsteini*). Furthermore, because of the conjunct occurrences of Tethyan conodonts and American radiolarian associations it has been proved that *M. hernsteini* occurs with the *B. deweveri* A. Z., far from the overlying *P. moniliformis* A. Z., commonly used to define the base of Rhaetian stage in North America, that seemingly coincides with the occurrence of *M. posthernsteini*. This coincident occurrence of *M. posthernsteini* and assemblage 1 of *P. moniliformis* A. Z. is supported by the collection of the *M. hernsteini/posterhernsteini* morphocline in the upper portion of *B. deweveri* radiolarian Zone that allowed to identify the first appearance datum (FAD) of *M. posthernsteini*.

At present, an important stratigraphical interval has been identified around the NRB that is characterized by some important bioevents. This interval involved the occurrences of conodont *M. posthernsteini*, *E. mosheri* morphotype A, the base of radiolarian *P. moniliformis* A. Z. and the global disappearance of bivalve genus *Monotis*. We suggest thus to consider this mostly coeval occurrences as bioevents to mark the base of the Rhaetian stage.

This study documents that the beginning of the radiolarian deposition occurred in different times in the various parts of the basin: it occurred inside the *M. hernsteini* biozone in those sections where the Transitional Interval is present (such as Sasso di Castalda and Mt Volturino), while it occurred only after the *M. ultima* Zone in the sections where the uppermost part of the Calcari con Selce Formation had deposited under euxinic conditions. Further studies are necessary to fully understand the physiography of the Lagonegro basin in the upper part of the Triassic and its detailed evolution up to the Triassic/Jurassic boundary.

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